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Sensors and Actuators 74 (1999) 246–250

SENSORS AND ACTUATORS A PHYSICAL

A thermoelectric converter for energy supply

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Abstract

A thermoelectric power generator in silicon technology is used for the energy supply of low power systems. An application is described generating an electrical power of 1.5 μW with a temperature difference of 10°C. With the generated electrical power it is possible to operate a small preamplifier and a sensor control system. For complexer applications a generator with a power in the region of 20 μW would be desirable.

Keywords: Energy supply; Thermoelectric energy converter; Silicon technology

1. Introduction

Small, independent and wireless systems for remote sensing, control, safety surveillance and metering are an important application of MEMS. Energy supply is mostly made with battery. This presents a number of severe disadvantages: the lifetime of batteries is limited which implies that the system has to be maintained or replaced after a few years. Furthermore, batteries contain chemical substances which are harmful to the environment. For this reason, the disposal of battery operated systems has to be controlled which is a very expensive procedure. Another common solution is the solar cell as it is used for small calculators or watches. If no light is available the small temperature differences which are present everywhere could be used to operate a thermoelectric converter. Therefore, small, inexpensive and efficient converters will gain importance as a replacement for batteries in many systems. This paper describes the development, technology and characterisation of a silicon thermoelectric energy converter.

2. Materials

Due to a number of works [1–9] the thermoelectric properties of bulk material and thin layers are well known. The crucial material parameter for a thermoelectric energy transformation is named 'figure of merit z' with

$$z = \alpha^2/(\lambda\rho) \tag{1}$$

where α is the Seebeck coefficient, λ the thermal conductivity and ρ the electrical resistivity. The largest values can be achieved by using semiconductor compounds such as Bi–Sb–Te thin films. When choosing the apt material technological aspects also have to be taken into account. Although the use of silicon as a thermoelectric material has the disadvantage of a high thermal conductance it has, however, the advantage of being a simple, reproducible and well established technology. For applications such as power supplies for controllers it may also be important to gain an appropriate voltage in the range of 1.5 V–2 V which can be achieved with silicon because of it's high Seebeck coefficient. Fig. 1 presents the thermoelectric power as a function of the resistivity of two types of silicon. Whereas c-silicon shows a high thermoelectric power between 300 and 1200 μV/K poly-silicon has just one of 150 to 450 μV/K. For silicon the dependence between α and ρ can be applied approximately [8]

$$\alpha_{Si} = mk/q \ln(\rho/\rho_0) \tag{2}$$

with $m = 2.6$, $\rho_0 = 5 \times 10^{-6}$ Ω m, k the Boltzmann constant and q the elementary charge. When putting the values α_{Si} (Eq. (2)) into Eq. (1) the maximum of the

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0924-4247/99/$ - see front matter
PII: S0924-4247(98)00298-2

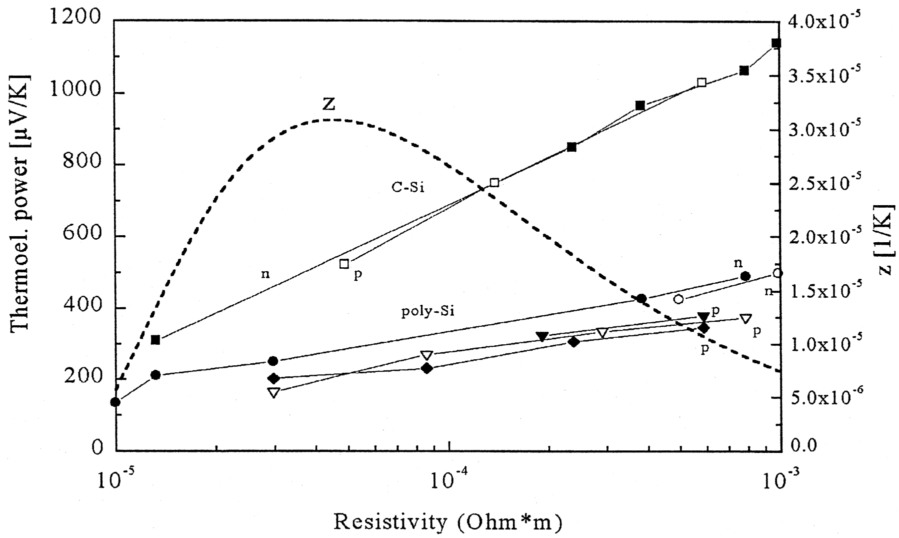

Fig. 1. Experimentally determined Seebeck coefficients of c-silicon as well as poly-silicon as a function of the electrical resistivity of the material at room temperature. 'Figure of merit z' for silicon.

thermic energy transformation for monocristalline silicon lies at a resistivity of $\rho = 4 \times 10^{-5}$ Ω m.

3. Layout and design

The component is designed for a system with low energy consumption. At an available temperature difference of 3 K between the contact points of the thermopile an electrical load of 1.5 μW should be generated. Since there are high demands on the generator particularly with respect to the thermal voltage (0.5 V/K ought to be achieved), silicon must be used to build up energy converter. If the doping concentration is chosen according to a specific resistance of $\rho = 4 \times 10^{-5}$ Ω m it is possible to achieve thermal voltage of 500 μm V/K and single contact. For the requested voltage of 0.5 V/K a thermopile of 1000 elements is necessary. In this case the advantage of silicon micromechanics, the structurizing in the μm-area allows the conception of a component with a reasonable size. Each element of the thermocouple is 7 μm wide and 500 μm long (Fig. 2) and consists of doped silicon and aluminium. The prototype presents a size of 11×1.5 mm.

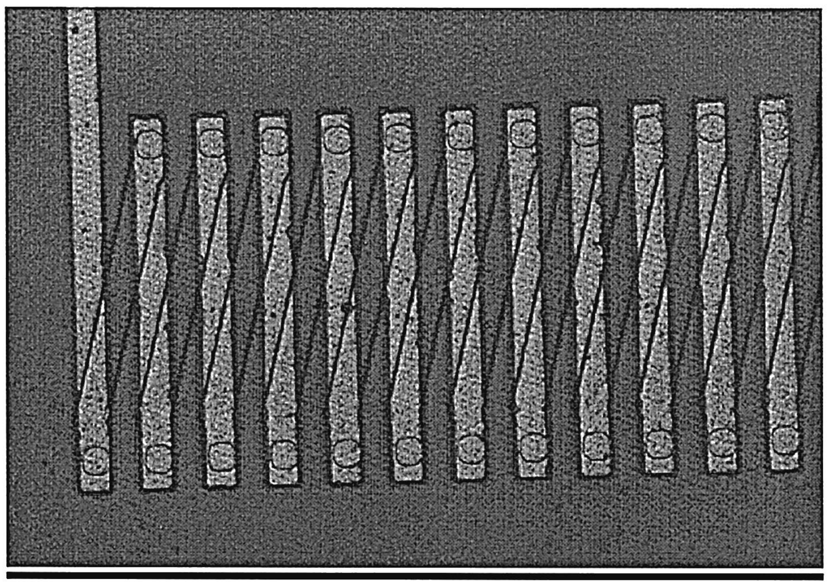

Fig. 2. Microscopic view of the implanted areas and the metal interconnections of the thermocouples.

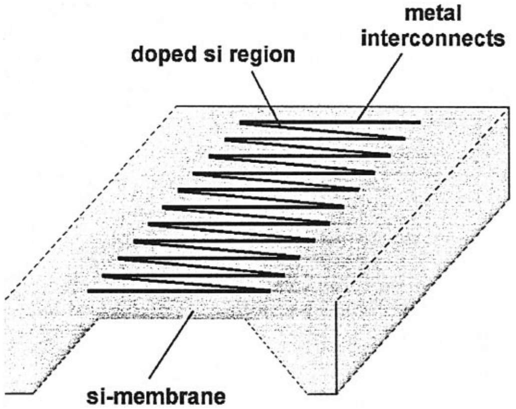

Fig. 3. Simple sketch of the device.

The 'figure of merit z' (Eq. (1)) presented above as being the main parameter for the thermoelectrical energy transformation applies merely for bulk material. Actually, in thin films and in silicon technology the thermopiles are mounted on a carrier material. Therefore, the cross-section for the energy transformation and for the heat flow are no longer the same. For the component described here the carrier material cannot be neglected anymore. A thermal difference of 1 K induces a heat flow of 600 mW/K. Most of this flow is parasitic because the thickness of the active region (1 μm doped zone) could be neglected in comparison to the one of the carrier material. A considerable reduction of this parasitic heat flow can be achieved placing the thermopile on a thin membrane (10 μm; Fig. 3). By this means the heat flow can be drastically reduced to 30 mW/K.

4. Assembly

For stabilization of the thin silicon membrane (10 μm) the edge cavity will be casted with a low heat adhesive

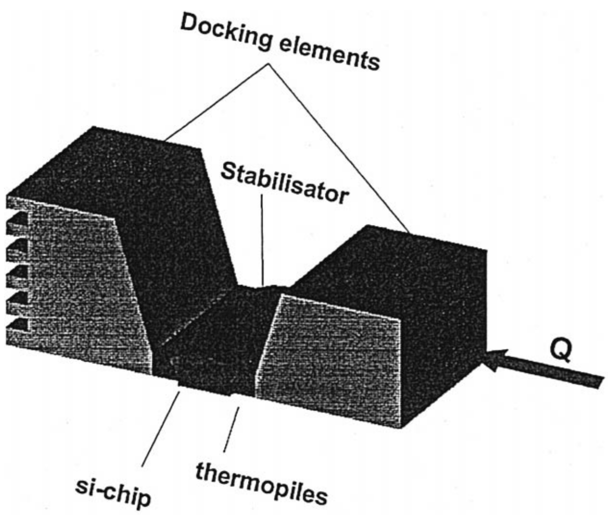

Fig. 4. Mounting of the thermoelectric generator. One side is connected to a heat source, the other one to a cooler. The thermocouples are placed on a thin (10 μm) silicon membrane.

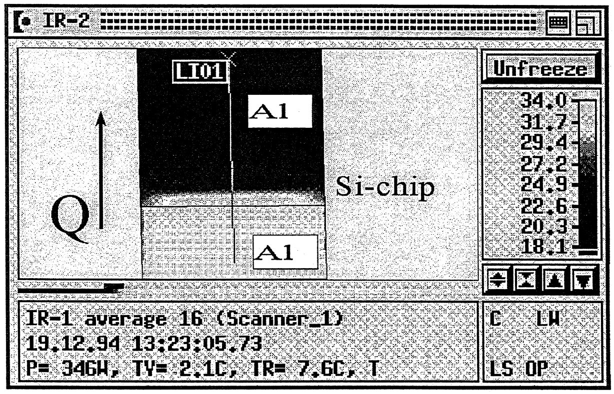

Fig. 5. Thermography of the surface of the device.

already on waferlevel. For building up a thermogenerator a suitable coupling of the silicon chip to the hot respectively cold connections is necessary (Fig. 4). The docking elements made of aluminium are bonded to the silicon chip with a adhesive technique.

For this purpose a great deal of developments were made because an effective energy transformation is only possible if the thermal resistance of the membrane is significantly larger than the thermal resistance $R_{\mathrm{th.bond.}}$ of the bonding gap between the silicon chip and the docking elements which is calculated as follows:

$$R_{\mathrm{th.bond.}} = d_{\mathrm{gl}}/(A\lambda_{\mathrm{gl}}), \tag{3}$$

where d_{gl} is the thickness of the gap, A its cross-section and λ_{gl} the thermal conductivity of the used adhesive.

In order to minimize $R_{\mathrm{th.bond.}}$ the use of a bonding with high heat adhesive is required. Moreover, it is absolutely important to obtain a very thin interface (d_{gl}). To measure the thermal characteristics of the component a thermographic system of AGEMA was used. The camera has a spatial resolution of approximately 20 μm. In addition, the surface was coated with a suspension containing titanoxid to improve its emittance. This makes it possible to measure the temperatures with an accuracy of ±0.5 K (Fig. 5).

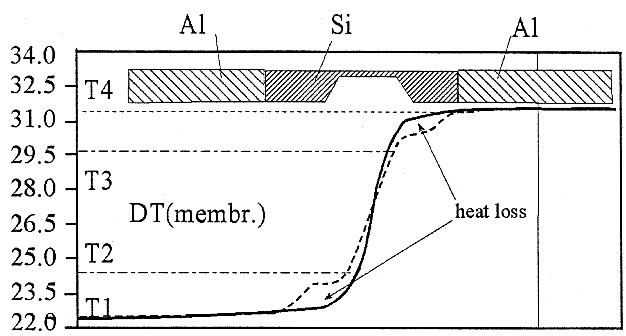

Fig. 6. Temperature profiles over the device surface measured with thermographic system. In contrast to a good interface (straight line) the dotted line refers to an unsuitable connection with thick glue film.

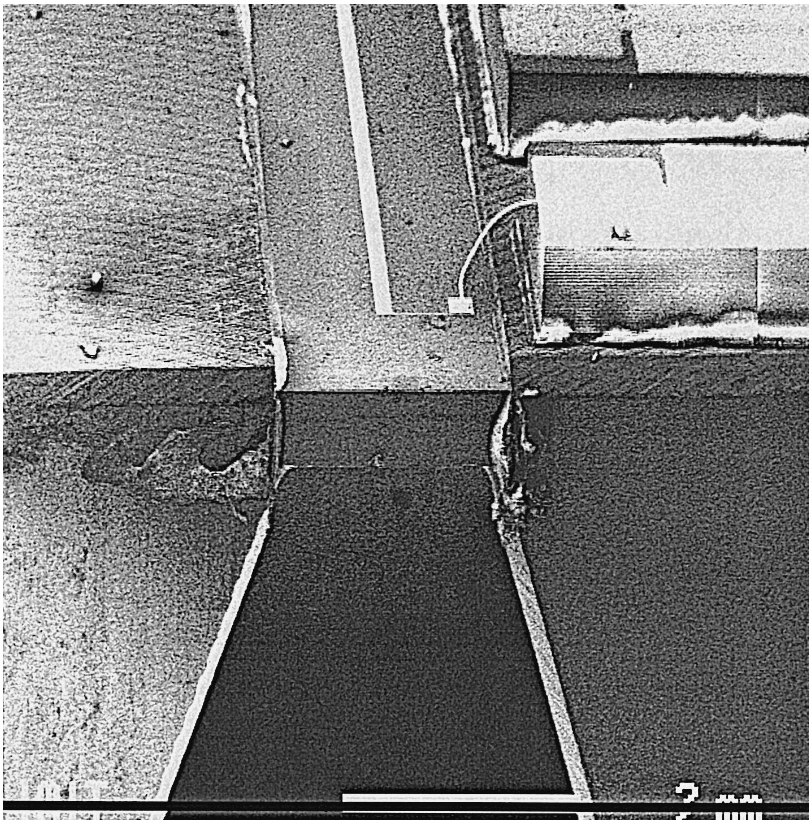

Fig. 7. SEM of the mounted converter.

Evaluation of thermographic pictures (Fig. 6) point out the difference between unsuitable devices and those with satisfied results. T4 − T1 is the thermal difference on the whole component whereas T3 − T2 is the actual temperature difference available on the membrane for the energy conversion. Fig. 6 shows clearly that there is a loss of temperature (approximately 30%) at the interfaces which present insufficient bonded points. After the testing of different adhesives a procedure is developed which avoids such losses. No further temperature differences can be noticed. The bonded areas are reproduced with a thickness in the order of 10 μm. By this method it is now possible to couple the micromechanic thermogenerator to the macro environment (Fig. 7) without any loss of temperature. The measured thermal resistance of the bonded area is about 0.5 K/W. Compared to this the resistance of the membrane is 27 K/W, i.e., by factor 50 higher. Having two bonded points a loss of approximately 5% results.

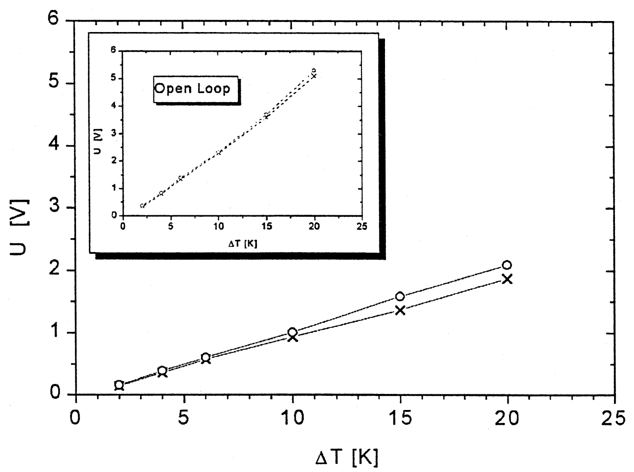

Fig. 8. Thermoelectric voltage V vs. temperature difference ΔT with a consumer resistance of $R_L = 750$ kΩ. The insert shows the open loop voltage.

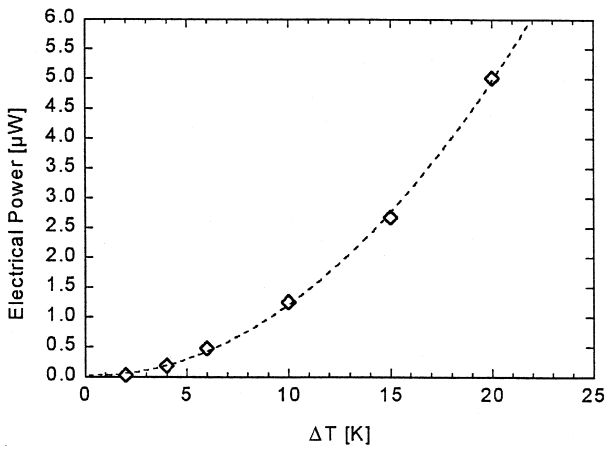

Fig. 9. External electrical power vs. temperature difference ΔT.

5. Measurements and results

The measured heat resistance of the doped Silicon is 12 $\Omega/\square$ with a depth of 1.2 μm. This leads to a resistivity ρ of 1.4×10^{-5} Ω m. The expected Seebeck coefficient is calculated to 300 μV/K (Fig. 1). The impedance of the thermopiles amounts to 900 kΩ.

As described in the previous chapter the temperature differences for the determination of the Seebeck coefficient were measured with the thermographic system. In this case it must be noticed that there are values with an error of up to $\pm15\%$ latter of which is due to the limited spatial resolution (25 μm) and the error in temperature measurement. Prototypes are produced with different thermopile lengths (150 μm, 300 μm, and 500 μm). The measurement of more than twenty components results in a Seebeck coefficient of 240 μm V/K $\pm$ 10%.

The comparison between the large and small membranes shows first of all a better efficiency of the large one. Small membranes show too high heat flow because of a smaller thermal resistance and furthermore present an increase of parasitic part via the stabilisator parallel to the membrane (Fig. 4) and consequently a decrease of the component efficiency.

To detect the capacity data the components are loaded with a consumer resistance of $R_L = 750$ kΩ. Fig. 8 shows the behaviour of two of such components. The measured values show same trend with a deviations of only 10%. Fig. 9 points out the proceeding course of the thermogenerator's performance. It shows that an electric power of 1.5 μW is reached at a temperature difference of 10 K.

6. Conclusion and outlook

Small, cheap and efficient thermoelectric converters will have important applications to replace batteries in many systems. This paper describes the development, technology, and characterisation of a silicon thermoelectric energy converter. It is demonstrated when a temperature difference of 10 K is applied, the device generates sufficient energy to operate a preamplifier and a small sensor. When the system is more complex, the power consumption rises. For this reason, a generator with a power in the region of 10–20 μW is suitable. At the moment, a second generation of the device is planned which will be 10 times more efficient. For this device the silicon parts of the thermocouples consist of thicker legs (10 μm high, 5 μm broad) which will be cut directly out of the wafer by high aspect ratio RIE dry etching. In this way, the impedance is drastically reduced and the externally extracted current rise. Furthermore the part of the parasitic heat flow can be drastically decreased because the whole membrane contributes to the energy conversion.

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H. Glosch, born in 1958, graduated from physical technologies at Heilbronn technical college in 1988. He was then at the research section of Kolben-Mahle, Stuttgart, until he came to IMIT in 1993. He is now concerned with the development of thermal sensors and actuators and is a requested consultant for physical measuring technology and measuring software.

Walter Lang studied physics at Munich University and received his Diploma in 1982 on Raman spectroscopy of crystals with low symmetry. His PhD in engineering at Munich Technical University was on flame-induced vibrations. In 1987 he joined the Fraunhofer Institute for Solid State Technology in Munich. In 1995 he became the head of the sensors department at the Institute of Micromachining and Information Technology HSG-IMIT in Villingen-Schwenningen, Germany. His areas of work are research and development in the field of microsensors, microstructuring, porous silicon technology and solid-state analytics.